CONTROL TECHNIQUES FOR POWER SYSTEM STABILISATION

MONALI MADHULITA(109EE0276)

GOURI SHANKAR DORA(109EE0269)

Department of Electrical Engineering

National Institute of Technology Rourkela

CONTROL TECHNIQUES FOR POWER SYSTEM STABILISATION

A Thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in "Electrical Engineering"

By

MONALI MADHULITA(109EE0276)

GOURI SHANKAR DORA(109EE0269)

Under the Guidance of

Prof.BIDYADHAR SUBUDHI

Department of Electrical Engineering

National Institute of Technology

Rourkela-769008 (ODISHA)

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DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ODISHA, INDIA-769008

CERTIFICATE

This is to certify that the thesis entitled "**Control Techniques for Power System Stabilization**", submitted by **Monali Madhulita (Roll. No.109EE0276) and Gouri Shankar Dora (Roll. No. 109EE0269)** in partial fulfillment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2012-2013 at National Institute of Technology, Rourkela is a bonafide record of research work carried out by them under my supervision and guidance. The candidates have fulfilled all the prescribed requirements. The Thesis which is based on candidates' own work, have not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

Place: Rourkela

Dept. of Electrical Engineering
National institute of Technology
Rourkela-769008

Prof. Bidyadhar Subudhi
Professer, Electrical Engineering

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MONALI MADHULITA
(109EE0276)

GOURI SHANKAR DORA
(109EE0269)

Dedicated to

To our parents who were a constant source of inspiration throughout our work

ABSTRACT

The conventional PSS was first proposed earlier based on a linear model of the power system to damp the low frequency oscillations in the system. But they are designed to be operated under fixed parameters derived from the system linearized model. Due to large interconnection of power system to meet the load demand brings in deviations of steady-state and non-linearity to power system. The main problem is that PSS includes the locally measured quantities only neglecting the effect of nearby generators. This is the reason for the advent of Wide area monitoring for strong coupling between the local modes and the inter-area modes which would make the tuning of local PSSs for damping all modes nearly impossible when there is no supervisory level controller. Wide area control addresses these problems by proposing smart topology changes and control actions. Dynamic islanding and fast load shedding are schemes available to maintain as much as possible healthy transmission system. It is found that if remote signals from one or more distant locations of the power system can be applied to local controller design, system dynamic performance can be enhanced. In order to attain these goals, it is desirable to systematically build a robust wide area controller model within an autonomous system framework.

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ABBREVIATIONS AND ACRONYMS

AVR	-	Automatic Voltage Regulator
PSS	-	Power System Stabilizer
CVCF	-	Constant Voltage Constant Frequency
AC	-	Alternating Current
DC	-	Direct Current
LFO	-	Low Frequency Oscillations
PID	-	Proportional Integral Derivative
MATLAB	-	MATrix LABoratory
dB	-	Decibel
Hz	-	Hertz
WAC	-	Wide Area Control
PMU	-	Phasor Measurement Unit
PDC	-	Phasor Data Concentrator
EMS	-	Energy management System
SCADA	-	Supervisory Control and Data Acquisition
LAN	-	Local Area Network
WAN	-	Wide Area Network
DFT	-	Discrete Transfer Function
NCS	-	Network Control System
WAMS	-	Wide Area Monitoring System
GPS	-	Global Positioning System
TCP/IP	-	Transmission Control Protocol/ Internet Protocol
SMIB	-	Single Machine Infinite Bus
TAFM	-	Two Area Four Machine

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Right from the birth of electricity from late 19^{th} century, many aspects regarding the utilization of electrical energy has evolved with time. Electrical energy being the most efficient energy in terms of its efficiency in transmission and utility sector (widely used induction machines). Electrical energy is the energy with maximum conversion efficiency and environment friendly. Right from the generation at some remote location till the distribution sector in cities and metros, the focus is on how to transmit power with high reliability and stability. Moreover the continuity of service is of maximum importance.

The main problems arise with the increase in power demand. For country like India with people residing mostly in villages and suburbs, supplying power to them has become the major responsibility for the leaders of our country. With increasing lengths of transmission lines and the power carried by them, there is a sharp increase in the probability of power fluctuations and faults. In times there may be a complete failure of power grids. So various power measurement devices and fault detection methodologies have been incorporated. Automatic Voltage Regulators are one such device which has been implemented. But still the grid suffers from its own hair line fractures (low frequency oscillations) which further lead to lower voltage fluctuations at generator level. This mini-error becomes excessively disastrous when sensitive loads at the distribution sector are adversely affected.

The fact that the power should be based on CVCF(Constant Voltage Constant Frequency) is very much relevant in the power map of India. With huge interconnection and high modern day reactive power consumption, complexities in power map of India is very evident. Maintaining both the voltage and frequency is of utmost importance.. The question comes where to start finding solution. If one can control the flow of energy in an efficient way right from its origin (Synchronous Generators in this case) then the solution becomes somewhat easy and economical. Moreover, controlling the alternators is not that simple. It contains numerous parameters and one has to choose a few to control and others should be compromised. Numerous Methodologies have been implemented but none as an ideal solution. This is a real challenge which motivated us to study and find out a viable and effective solution to optimize the process.

1.2 AUTOMATIC VOLTAGE REGULATOR

Constant voltage at the generator terminals is essential for satisfactory main power supply. A voltage regulator is implemented to automatically maintain a constant voltage level. A voltage regulator may be incorporated as a simple "feed-forward" design or may include negative feedback control loops. It may use an electromechanical mechanism, or as electronic components. Depending on the design, it can be used to regulate one or more AC or DC voltages. In automobile alternators and central power station generator plants, voltage regulators can control the output of the system. In an electric power distribution system, voltage regulators are installed at a substation or along distribution lines so that all customers receive steady voltage independent of how much power is drawn from the line. An AVR is at the heart of devices called power conditioners. The typical power conditioner is an automatic voltage regulator combined with one or more other power-quality capabilities such as:

- Surge suppression,
- Short circuit protection (circuit breaker),
- Line noise reduction,
- Phase-to-phase voltage balancing,
- Harmonic filtering, etc.

Anyone receiving power from an electric utility will see the nominal incoming voltage level (e.g. 220V) change over the course of a day to a small or major percentage. There can be many factors contributing to the amount of voltage level fluctuation observed including:

- location on the distribution line,
- presence of numerous electricity consumers,
- presence of utility voltage regulating equipment,
- seasonal variations on overall system voltage levels,
- load factor upon local transmission and distribution system, etc.

Voltage levels are often highest during the night time hours and weekends when the electrical demand is minimal and are lowest weekday afternoons when the demand for electricity is at its peak. Most electric utility sectors in India try to maintain the voltage level within plus or minus 5% of the nominal voltage level (e.g. 220V +/-5%). Hence AVRs are highly helpful for this respect.

1.3 THE EXCITATION SYSTEM OF THE ALTERNATOR

We proceed as per the schematic diagram of the excitation system which we shall primarily use in this project to design the power system stabilizer [4].

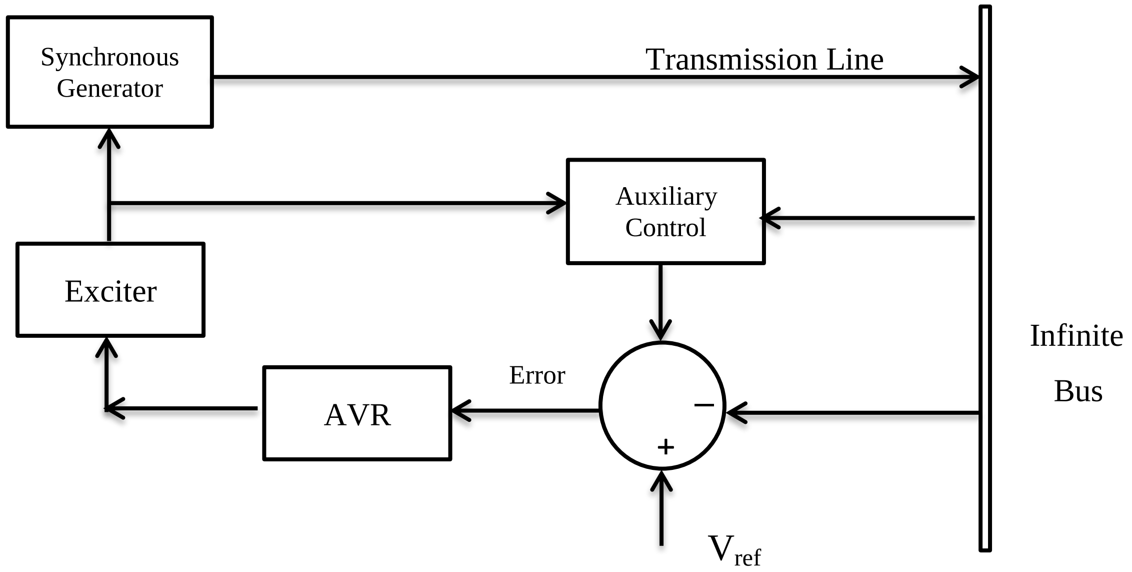

Fig 1.1 Schematic of an Excitation System

A modern excitation system contains components like Automatic Voltage Regulators (AVR), Power System Stabilizers (PSS), and filters, which help in stabilizing the system and maintaining almost constant terminal voltage and constant frequency. These components can be analog or digital depending on the viability, complexity, and operating conditions. The final aim of the excitation system is to reduce swings due to transient rotor angle instability and to maintain a constant voltage. To do this, a step voltage is fed as a reference voltage, which is taken to be a constant. The AC voltage is first converted into DC voltage by rectifier units and is fed to the excitation system via its components like AVRs, PSSs etc. The AVR sends actuating signal which actuates the excitation by the exciter of the Alternator. This is a continuous process and has got certain limitations. Meanwhile, there is a so called Auxiliary control which may be represented by a PSS in real time application. The PSS takes up data from infinity bus directly. The PSS deals with small voltage fluctuations and does fine adjustment as required. It provides output to the comparator block directly and hence plays a significant role in fine tuning of error signal.

1.4 OVERVIEW OF THE PROPOSED WORK DONE

Rigorous Study has been done to carry out the project which includes papers on automatic voltage regulators, excitation system, power system stabilizers, tuning of power system stabilizers, etc. Reference [1] gives an overview about the details of excitation system and the development of power system stabilizers, its use and applications. Reference [2] gives us the basic idea of modeling of power system stabilizers, multi machine design, and robust genetic algorithms. Reference [3] describes about the different kinds of stability issues to be considered while designing a power system stabilizer. Rotor angle, Voltage and Frequency Stability are taken into consideration. Reference [4] tells about the pole placement design technique for power system stabilizer. References [5] describe various methods developed for designing power system stabilizers such as fuzzy logic, model predictive control etc. Reference [6] made us understand the basics of power system stabilizer and its different parameters. Reference [7] shows in detail other conventional design algorithms. Reference [8]- [9] give an account of neuro fuzzy logic technique. Reference [10] helped us to design the wide area measurement systems and a brief description of phasor measurement units. References [11]-[12] gave a detailed knowledge about networked control systems and different problems associated with them. Network induced delays, Data packet dropout, Data packet dis-ordering are the problems under study. Reference [13] gives an overview of modeling delay in a network controlled system. Reference [14] demonstrates a robust damping control design for multiple swing modes damping in a power system model using global stabilizing signals. Reference [15] proposes a packet-based control which takes advantage of the characteristic of the packet-based transmission in a networked control environment. Reference [16] deals with the study and analysis of power system stabilizers using Matlab simulations. Reference [17] provides us with all the practical values of a standard power system with only one generator. It basically fives the state space parameters of the system. Reference [18] studies the behavior of network after introduction of delays.

1.5 THESIS OBJECTIVES

The following are the objectives are hopefully achieved at the end of the project.

- To review different approaches to PSS Design.
- To design and implement PSS for SMIB system using Root Locus Approach.
- To design and implement PSS for SMIB system using Frequency Response analysis.
- To design and implement PSS for SMIB system using State Space Methods analysis.
- To review compare the above mentioned methods.
- To study modern day approach of Power System Stabilization.

1.6 ORGANISATION OF THESIS

The thesis is organized into five chapters. Each chapter is different from the other and is described along with the necessary theory required to comprehend it.

Chapter1 analyses the problems developed after the demand started increasing gradually and complexity of power system network simultaneously increased. The introduction of AVR to have controlled output voltage and frequency at the consumer end has failed to tune low frequency oscillation that remain in the network for long and can harm the system. The excitation system of the alternator is studied to have better understanding on how this works. To damp out the low frequency oscillations PSS was introduced to have better performance and stability.

Chapter2 describes the basic structure of a PSS. The various components involved are washout filter, dynamic compensator, torsional filter, limiter etc. Each block has its own advantages and use which is vividly described in the chapter. Then various conventional design techniques are studied so that better analysis is possible. The methods can be implemented to study various aspects of PSS. The excitation system of an alternator system is mathematically modeled in this section. MATLAB Simulink design is also provided there. The various input and output parameters are selectively chosen.

Chapter3 basically deals with methods implemented in designing the PSS. The system where we implement our method is SMIB (Single Machine infinite bus) where a single machine is connected to an infinite bus. The PSS design methods taken into consideration are Root Locus Technique, Frequency Response Method, and State Space Analysis. The design of AVR and PSS are done simultaneously from which we can know the requirement of either lag or lead or lag-lead compensators. Finally a comparison is done among the methods and the best result is to be implemented practically.

Chapter4 deals the introduction of wide area monitoring system for better functioning of the system. PSS was only able to control the oscillations in local area but now-a-days, a large area is to be considered due to huge demand. Therefore network control systems are incorporated into the systems. . Dynamic islanding and fast load shedding are schemes available to maintain as much as possible a healthy transmission system. New technologies like PMU's and SCADA measurement systems make easier detection of faults and better analysis of a real time system. PMU quantities are collected and concentrated for further exploitation in a PDC (Phasor Data Concentrator). The structure of a wide area monitoring system is described. Networked Control System Model is also mentioned and the problems discussed are Network induced delays, Data packet dropout, Data Packet disordering. Lyapunov's stability criterion is the most basic method for determination of stability of non-linear or linear time-varying systems. This algorithm is also implemented in our study.

Chapter5 concludes the work performed so far. The possible limitations in proceeding research towards this work are discussed. The future work that can be done in improving the current scenario is mentioned. The future potential along the lines of this work is also discussed.

CHAPTER 2

POWER SYSTEM STABILIZER

2.1 INTRODUCTION

Power System Stabilizer (PSS) is introduced in generators to give that fine adjustment to damp out power oscillations that are referred to as electromechanical or low frequency oscillations (LFO) [1]. A PSS detects the changing of alternator output power, controls the excitation voltage, and also reduces the power swing rapidly. It does that by providing supplementary perturbation signals in a feedback path to the alternator excitation system. The PSS thus contributes to the enhancement of small-signal stability of power systems.

The transient stability of a system can be improved by providing suitably tuned power system stabilizers on selected generators to provide damping to marginally stable oscillatory system. Suitably designed Power System Stabilizers (PSS), will introduce a component of electrical torque in phase with generator rotor speed deviations resulting in damping of low frequency power oscillations in which the generators participate. The input to power system stabilizer may be one of the locally available signals such as changes in shaft speed, rotor frequency, accelerating torque or any other suitable parameter. This stabilizing signal has to be compensated for phase and gain to result in adequate component of electrical torque that results in damping of rotor oscillations and thereby enhance power transmission and generation capabilities. State-space techniques classified under Dynamic Stability Studies or classical control theory such as Root Locus techniques or Bode plots are used to determine suitable parameters for power system stabilizers. The design may be verified with a transient stability analysis for practical system disturbances.

In today's practical power systems, the small-signal stability problem mainly includes insufficient damping of system oscillations. The basic function of a Power System Stabilizer is to extend the stability limits by modulating alternator excitation, to damp the oscillation of alternator’s rotor relative to each other. The oscillations of concern typically occur in the frequency range of approximately 0.2 to 3.0 Hz. The PSS basically converts the over frequency part to the respective constant frequency and then the reference voltage is found. This is actually fluctuating in real time, hence PSS provides and actuating signal in reference to given above three outputs of the generator and then controls it by providing the exact error to the AVR block.

2.2 PSS BLOCK DIAGRAM

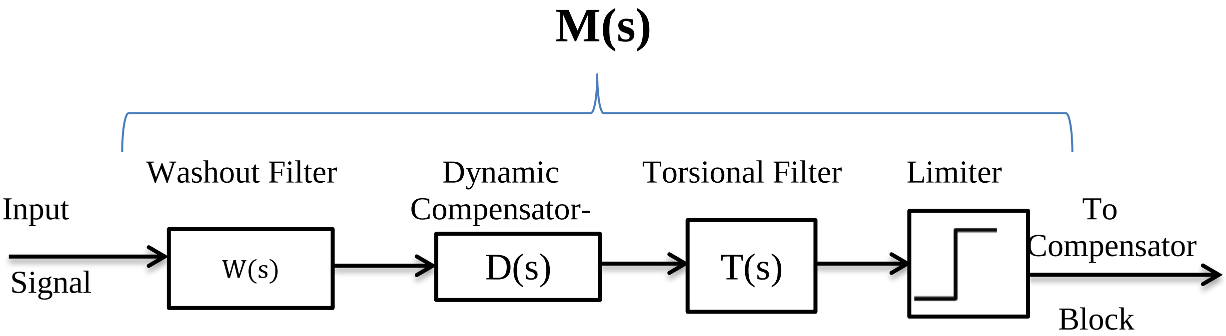

Fig 2.1 Block Diagram of a Power System Stabilizer

The block diagram used in industry is shown in Fig. 2.1. It consists of a dynamic compensator, torsional filter ,washout circuit, and limiter. The washout circuit is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS should respond only to transient variations in the input signal (rotor slip) and not to the dc offset in the signal [2]. The washout circuit acts essentially as a high pass filter and it must pass all frequencies that are of interest. Implementation of a power system stabilizer implies adjustment of its frequency characteristic and gain to produce the desired damping of the system oscillations in the frequency range of 0.2 to 3.0 Hz. The transfer function of a generic power system stabilizer having washout circuit, dynamic compensator and a torsional filter may be expressed as:

$$\mathrm{M(s)} = K_s \frac{\tau_w s(1+sT_1)(1+sT_3)}{(1+s\tau_w)(1+sT_2)(1+sT_4)} \qquad (1.1)$$

where K_s represents stabilizer gain,

τ_w represents time constant of Washout Filter,

T_1 & T_2 represents the time constant of Dynamic Compensator,

T_3 & T_4 represents the time constant of Torsional Filter.

The output of PSS must be limited to prevent a circumstance when the PSS itself acts to counter the action of AVR. To begin with, simple analytical models, similar to that of a single machine connected to an infinite bus system (SMIB), can be useful in determining the frequencies of local mode oscillations. Power system stabilizer should also be designed to provide stable operation for the weak power system conditions and associated loading [3].A designed stabilizer must ensure for the robust performance and satisfactory operation with an external system reactance ranging from 20% to 80% on the unit rating [3].

2.3 REVIEW OF DIFFERENT PSS TECHNIQUES

1. **PID Control Approach**

   PID is used for stabilization in the system. The input is the change in speed from the generator. The aim is to control the angle between load and speed of generator. The PSS parameters are tuned from Open loop transfer function to close loop based on Fuzzy logic. Therefore, the open loop transfer function and maximum peak response parameter make the objective function which is used to adjust PID parameters.

2. **LAG-LEAD Design**

   The washout block is used to reduce the over response of the damping during extreme events. Since the PSS produces a component of electrical torque in phase with speed deviation, phase lead blocks circuits can be used to compensate for the lag between the PSS output and the control action(hence lead-lag). It proves its value when the disturbance is multi natured.

3. **Pole Placement Method**

   The pole placement method is applied to tune the decentralized output feedback of the PSS. The objective function is selected to ensure the location of real parts and damping ratios of all electro mechanical modes. At the end of the iterative process, all the electromechanical modes will be moved to the region if the objective function converges to zero [7][8].

4. **Model predictive Control**

   It can handle non linarites and constraints in saturated way for any process model. In these techniques an explicit dynamic model of a plant is used to predict the effect of future actions of manipulated variables on the output.

5. **Linear Matrix Inequalities:**

   The important feature is the possibility of combining design constraints into a single convex optimization problem.it is used in many engineering related problems. The condition that the pole of a system should lay within this region in the complex plane can be formulated as an LMI constraint.

6. **Linear Quadratic Regulator**

   These are well known as compared to lag-lead stabilizers. This is used as a state feedback controller. A co-ordinated LQR design can be obtained with Heffron-Phillips Model and it can be implemented by using the information available within the power system. During the presence of faults even these methods prove to be stable [8].

7. **Genetic Algorithm**

   Genetic algorithm is independent of complexity of performance parameters and to place the finite bounds on the optimized parameters [8]. As a result it is used to tune multiple controllers in different operating conditions or to enhance the power system stability via PSS and SVC based stabilizer when used independently and through different applications.

8. **Fuzzy Logic Control**

   These are rule based controllers. The structure of this logic resembles that of a knowledge based controller; it uses principle of fuzzy set theory in its data interpretation and data logic. It has excellent response with small oscillations. The controller is robust and works effectively under all types of disturbance. It has very short computation time [9] [10].

9. **Neural Network**

   Neural Network is used to approximate the complex non-linear dynamics of power system. Magnitude constraint of the activators is modeled as saturated non-linearities and is used in Lyapnov's stability analysis [9] [10]. The overshoot is nearly same as conventional PSS but settling time is drastically reduced.

10. **Anfis PSS**

    The actual design method may be chosen based on real time application and dynamic performance characteristics. If the training data and algorithm are selected properly then good performance can be observed.

2.4 PSS: THE EXCITATION SYSTEM MODEL

SIMULINK™ model of the single machine excitation system [5] is given below:

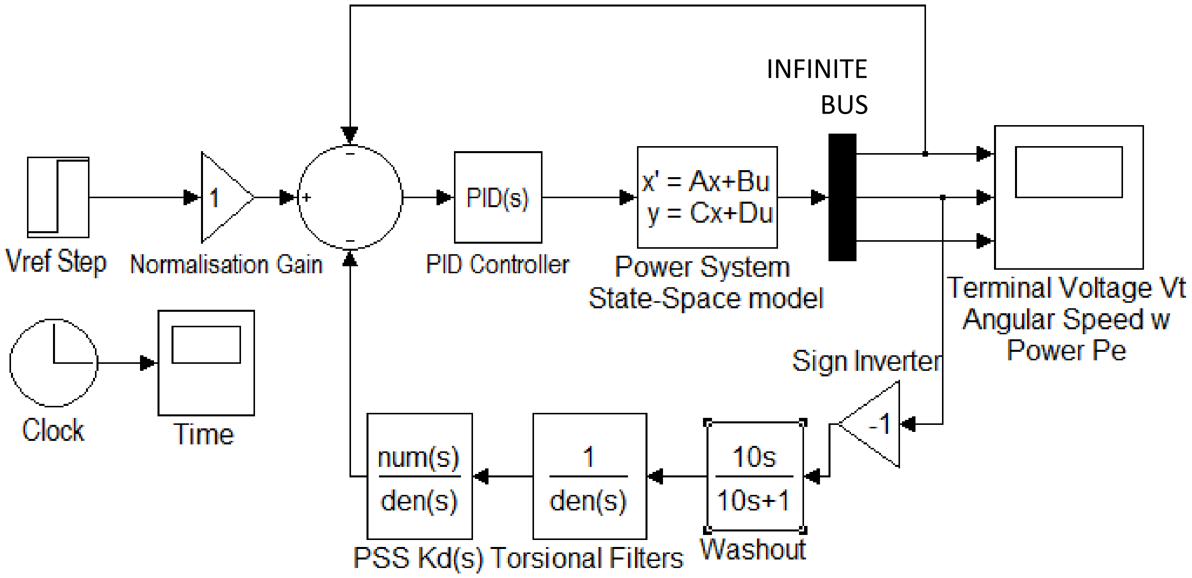

Fig 2.2 SIMULINK model of the Single-machine infinite bus [SMIB].

The Power System Model

The state space equations are

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{1.2}$$

$$\Delta y = C\Delta x \tag{1.3}$$

where state variables $x=[\delta \quad \omega \quad E'_q \quad \psi_q \quad E'_d \quad \psi_d \quad V_T]^T$

Output variables $y=[V_T \quad \omega \quad P_e]$

Input variable $u=V_{ref}$

where, δ= rotor angle in radian.

ω= Angular frequency in radian/sec.

ψ_d, E'_d= Direct axis flux and field.

Ψ_q, E'_q= Quadrature axis flux and field

V_T= Terminal voltage

P_e= Power delivered to infinite bus by the generator.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The methodology basically deals with methods implemented in designing the PSS. The methods are first applied in software called MATLAB Simulink, where they are virtually represented by blocks and the whole virtual system is made to run in real time. In direct implementation a minute error can lead to devastating results. Matlab provides a platform where we can observe in real time how the results change with change in parameters. Matlab contains inbuilt power system tools which can be directly collected from its library. The system where we implement our method is SMIB (Single Machine infinite bus) where a single machine is connected to an infinite bus. The model is clearly represented in section 2.4 and the parameters can be achieved from appendix. We proceed first by conventional design which forms the basis of every Power system stabilizer design. We then proceed to upper version in next chapter.

3.2 DESIGN OF AVR AND PSS USING COVENTIONAL METHODS

In our model of SMIB, we have two aspects of design namely:

a) Voltage regulator (AVR)
b) Power system stabilizer (PSS)

The power system stabilizer designed here adopted has been grouped under three heads:

1. Root-Locus approach (PID controlled Lead/Lag compensator)
2. Frequency response approach (Lead-Lead compensator)
3. State-Space approach (Observer based Controllers)

For each of the above method first the AVR is designed. AVR provides course tuning of the voltage control. AVR are implemented in feed forward open-loop model itself. Then we used the designed AVR model and implement the PSS in negative feedback loop. The PSS had initially the torsional filter, washout filter and limiter. All we are doing is designing the dynamic compensator for effective implementation of the system. The transfer function of the filters and limiter are fixed while that of the dynamic compensator varies from method to method. Each method has its own unique set of algorithms and produces a different result. At the end of the chapter we compare each of methods with their different pros and cons

3.2.1 ROOT LOCUS METHOD

The root locus implementation method of the PSS involves the following steps

(a) Design of the AVR:

The given 7th order system has a mixed proportion of dominant and nominal poles. Controlling the dominant poles stabilizes the disturbances. In this case a pair of dominant conjugate pole pairs is taken the AVR is analyzed.

STEP 1:

- 0.1p.u step input as V_{ref} is generally taken.
- Proportional Controller is implemented for AVR and simulation is done for 10 seconds for different values of K_p starting from K_p=1.

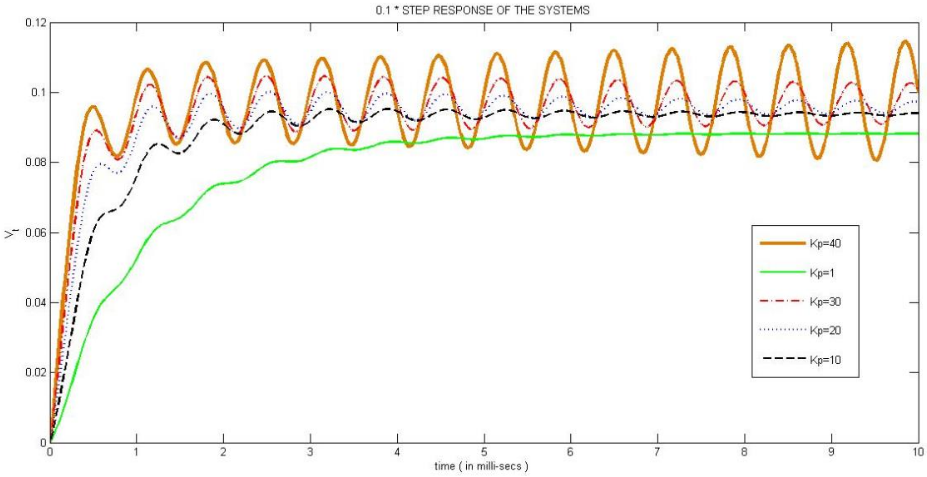

Fig 3.1 Voltage Response with different value of K_p

STEP 2 :

- root locus plot of the VR loop is made using only Proportional Controller.

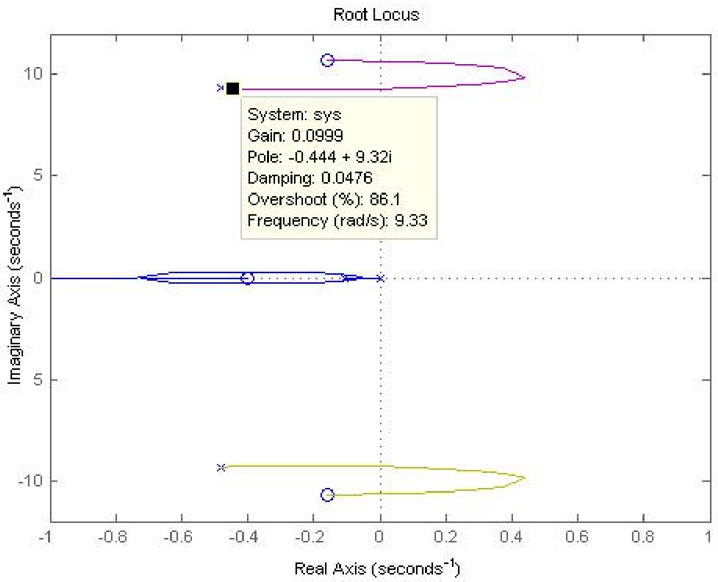

Fig 3.2 Root locus of Voltage Regulator forward loop showing dominant poles

STEP 3 :

- As K_p increases the closed loop step response becomes faster and steady step error becomes smaller but oscillations become more dominant.
- One can next implement a PI controller for AVR having the transfer function,

$$V(s) = K_p\left(1 + \frac{K_i}{s}\right) \quad (1.4)$$

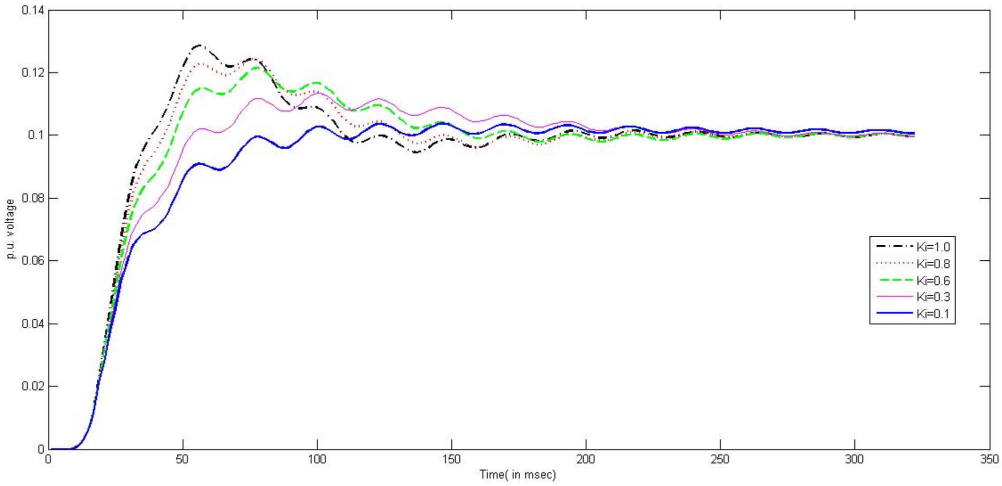

Fig 3.3 Represents the response of Open loop system (PSS feedback is open) for different values of Ki keeping K_p as constant (K_p=30)

- The design is made in accordance with : $\mathbf{t_r < 0.3}$ sec and $\mathbf{M_p < 12\%}$ (1.5)
- One gets $\mathbf{K_i = 0.6}$ which satisfy the above specifications.

b) ***Design of PSS****:*

STEP 4 :

- The PSS was then incorporated in the feedback loop.
- The Root locus was plotted & the angle of departure was calculated as **50.64** deg.

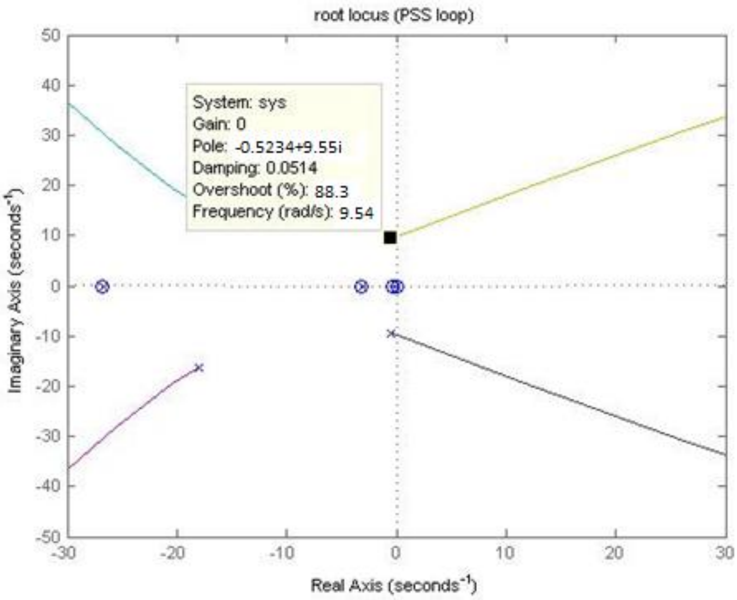

Fig 3.4 Root locus of PSS loops showing the dominant complex poles.

- We observe the dominant complex poles are at **(-0.5234+9.55i, -0.5234 -9.54i).**
- We need to make angle of departure **Φ_P=180º** for perfect damping.

STEP 5 :

- Based on this angle we need lead-lead compensators (here 2 in number) :

$$P(s) = K[K_a\left(\frac{s+z}{s+p}\right)][K_a\left(\frac{s+z}{s+p}\right)] \quad (1.6)$$

- We use two lead compensators in series each adding an angle of 64.8º. K is chosen from the root locus plot of the final PSS loop such that damping ratio **$\zeta > 18\%$.**
- From Root-Locus we calculate the zeroes and poles of the transfer function along with the required gains.

z= 3.5 **p= 24** **Kα= 13.24** **K= 0.52** (1.7)

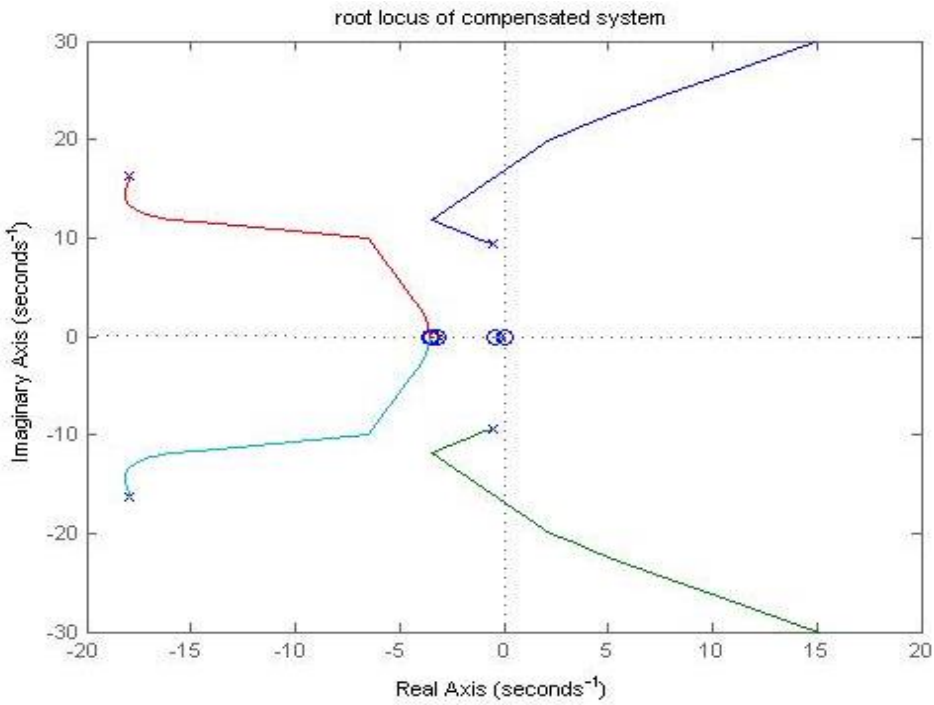

Fig 3.5 Root locus plot of the final PSS loop

- The compensated lead-lead compensator can be given by

$$P(s) = 0.52[13.24\left(\frac{s+3.5}{s+24}\right)][13.24\left(\frac{s+3.5}{s+24}\right)] \quad (1.8)$$

STEP 6 :

- Next, we implement this PSS and simulate the response.

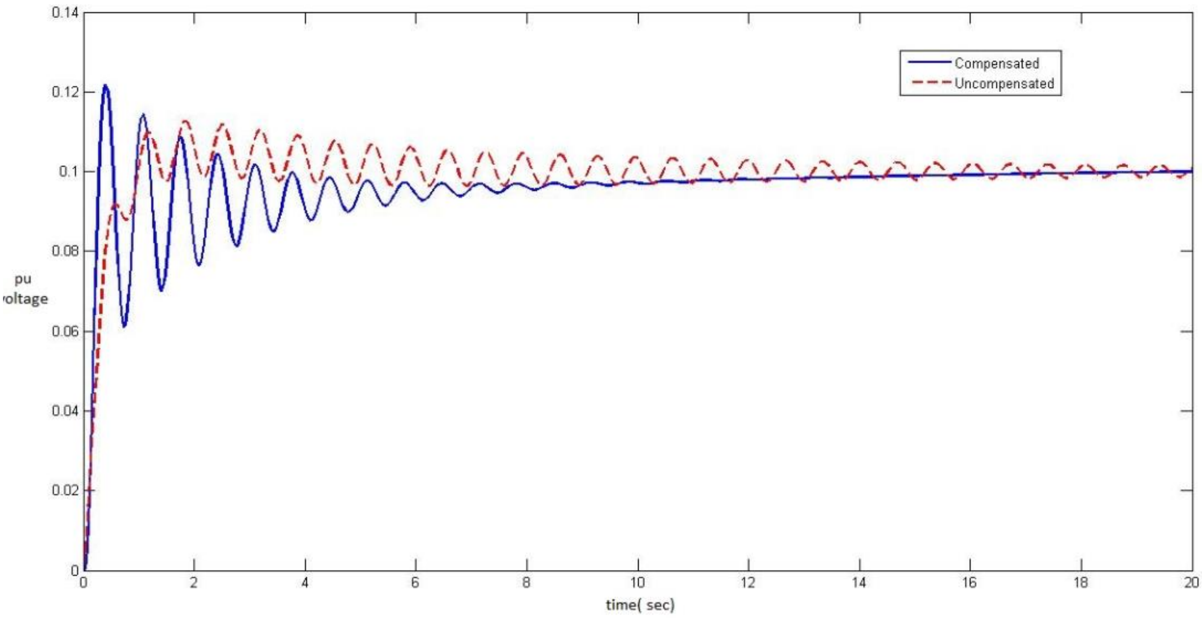

Fig 3.6 Comparison of voltage responses with and without PSS

- We observe that PSS improves the performance as compared to uncompensated one.

We can clearly observe that the PSS compensated model clearly provides superior performance in terms of rise time, settling time, peak overshoot and steady state error. Each of the parameters is optimized in their own way and system performance is improved.

3.2.2 FREQUENCY RESPONSE METHOD

The AVR and PSS are designed as per the following algorithm

a) ***Design of the AVR:***

STEP 1 :

- First, we observe bode plot response of the open-loop Power system.

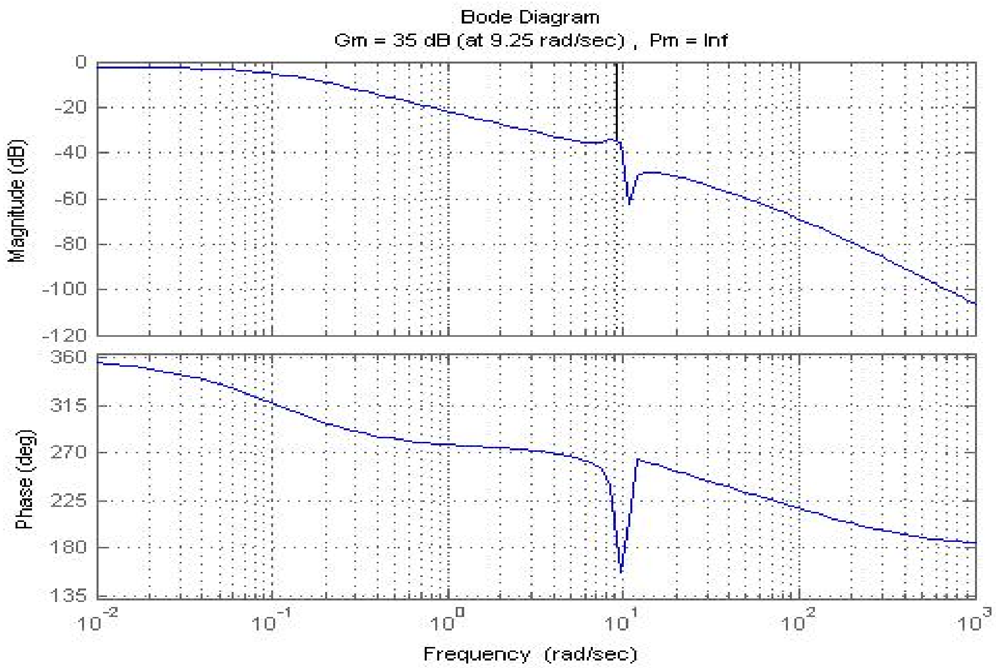

Fig.3.7 Frequency response of an uncompensated AVR Loop

- We find that:

  - Gain margin G_m = 36dB .
  - Phase Margin = infinite
  - DC gain= -2.69dB (0.78)

STEP 2 :

- The design specification require the *DC gain > 200 (=46dB) & phase margin > 90º.*

- Required gain K_c=10^((200+0.78)/20) = 276 .New gain crossover frequency= 5rad/s.

- This requires a lag-compensator for AVR, having transfer function:

$$V(s) = K_l[\frac{s+z}{s+p}] , \tag{1.9}$$

where $K_l = [\frac{K_c}{\beta}]$ $p = \frac{z}{\beta}$

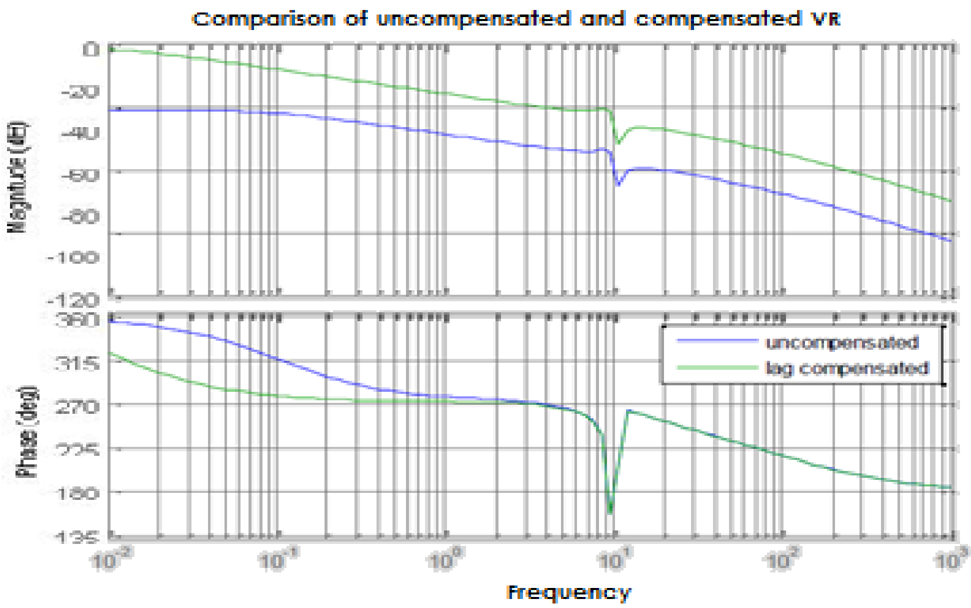

Fig. 3.8 Comparison of frequency response with and without VR loop

- Now, the lag required at 5rad/sec is -18dB. Hence,

$$20log\frac{1}{\beta} = -18 \qquad \text{i.e. } \beta = 8 \tag{1.10}$$

- We choose the corner frequency f=0.1 to make the system faster. So, z =0.1 .Hence

p=0.1/8 = 0.0125, K_l= 276/8 = 33.25.

STEP 3:

- Thus the final AVR is:

$$V(s) = 33.25[\frac{s+0.1}{s+0.0125}] \tag{1.11}$$

- We plot the compensated AVR and compare it with the uncompensated system.

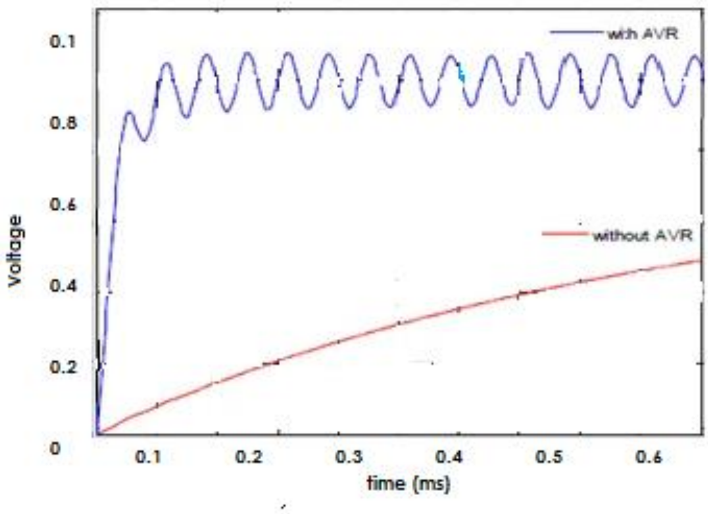

Fig 3.9 Voltage response of the lag compensated VR

- **Rise time t_r= 0.45sec. Maximum overshoot M_p= 8.56%**

*b) **Design of the PSS:***

STEP 4 :

- We generate the state-space model from V_{ref} to ω with the regulation loop closed.
- We isolate *Q(s)* resulting state-space model has input Δω and output τ (balancing torque). Thus we get A_{33}(5*5 matrix), a_{32} (5*1 vector), a_{23}(1*5 matrix).

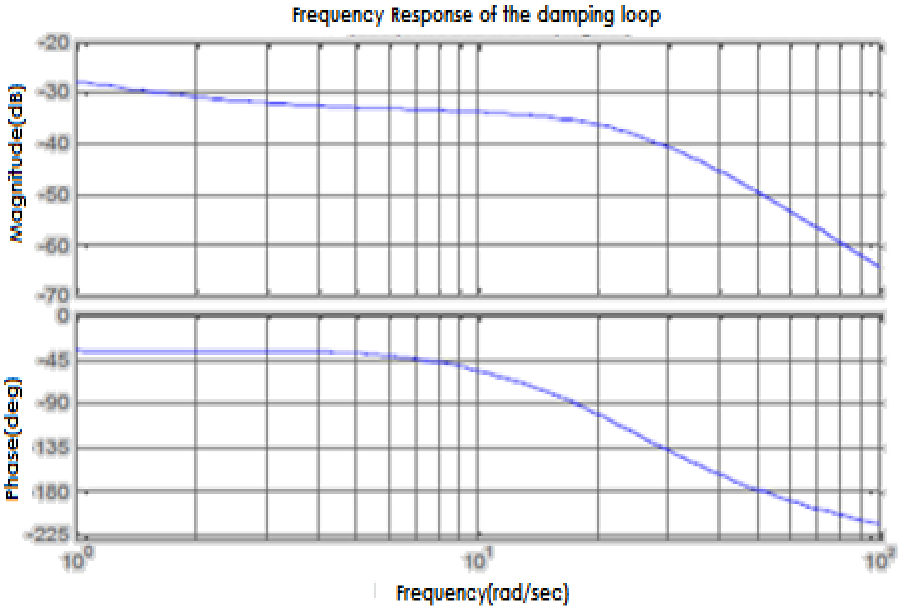

Fig 3.10 Frequency response of the Damping Loop

- Phase at 2rad/sec = -40° while Phase at 20 rad/sec = -102°.
- We require increasing phase of the feedback loop which will add pure damping to the dominant poles.
- Hence we require a lead compensator of the given by

$$P(s) = K[K_a\left(\frac{s+z}{s+p}\right)][K_a\left(\frac{s+z}{s+p}\right)] \quad , \quad \text{where } K_a = [\frac{K_c}{\propto}] \tag{1.12}$$

- The parameters of the transfer function were obtained by the constraints- Addition of phase of 40° at 2 rad/sec, 65° at 12 rad/sec and 102° at 20 rad/sec.

STEP 5 :

- Maximum phase addition Φ_m is at 20 rad/sec=102°. This is too large for a single lead compensator: We use two identical lead-compensators in series each compensating 51°.
- From the relation :-

$$\sin \Phi_m = \frac{1-\propto}{1+\propto}, \quad \text{we get } \alpha = 0.1254 \tag{1.13}$$

$$K_a=\frac{1}{\alpha} = 8 \quad T== \frac{1}{\sqrt{\propto w}} = 0.141 \quad z=\frac{1}{T} = 7.08 \quad p=\frac{1}{\alpha T} = 56.47 \tag{1.14}$$

- From the root locus plot, we get K for ζ **>12%, K=6**.

$$P(s) = 6[8\left(\frac{s+7.08}{s+56.47}\right)][8\left(\frac{s+7.08}{s+56.47}\right)] \qquad (1.15)$$

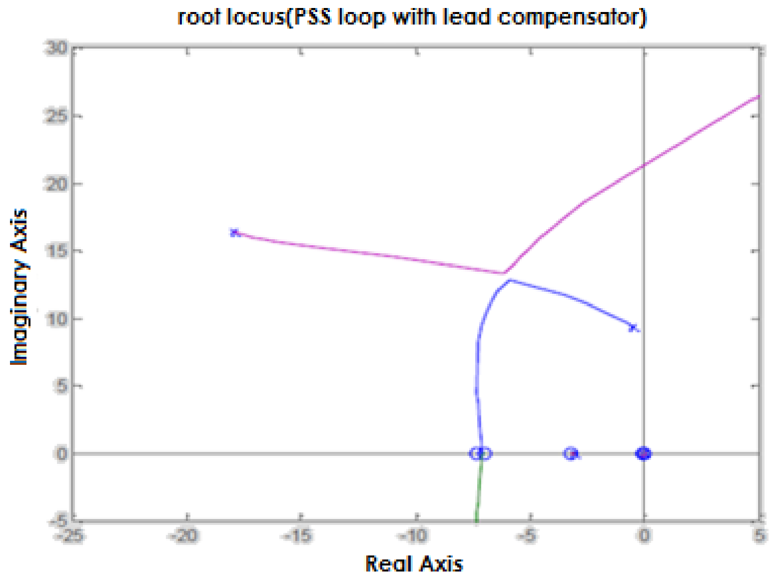

Fig 3.11 Represents the root locus plot of the damping loop

- The dominant real pole is -0.1064.For the controller design, we have to make this dominant pole faster and steady state error zero. We choose the shifted pole at **-2.0+0j** and leave the other poles unchanged. Then one can implement this PSS and plot the step response..

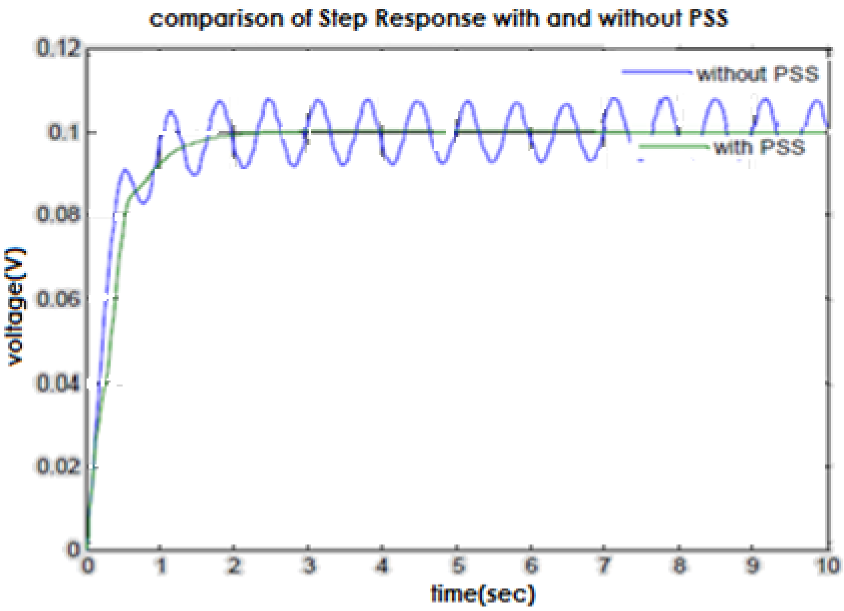

Fig 3.12 Output Response of the final signal.

The final model clearly shows that the system with PSS provides excellent performance in terms of steady state error and settling time.

3.2.3 STATE-SPACE METHOD

The state space design involve designing full state observers using pole placement to measure the states and designing the controller such that the closed loop poles lie in the desired place.

a) ***Design of the AVR:***

STEP 1:

- One can obtain the 1-input 1-output model of SMIB from V_{ref} to V_{term}. Hence, one gets A_1 (7*7 matrix), B_1 (7*1 vector), C_1 (1*7 matrix), and D_1(1*1) as given earlier **.**
- We find the open loop poles of this system :

(-114.33 , -35.37 , -26.72 , -0.48±9.33j , -3.07 , -0.1054)

- Using K_c=acker(A_1, B_1, modified poles), we design full-order observer to measure states.
- We choose observer dominant pole to be far from the jw axis, hence it decays very fast.
- We take it to be **-8.0+0.0j** and leave other poles unchanged.

STEP 2:

- Again, using MATLAB, we find the observer gain matrix K_o. K_o= place(A_1', C_1', modified poles)' . Finally we find the state space representation and the transfer function:

  A_o= A_1-(K_o*C_1) – (B_1*K_c)

  B_o= K_o

  C_o= K_c

  D_o= 0

- We get the 7_{th} order observer-controller .

$$\frac{405.6s^6+7.32e4s^5+3.588e6s^4+6.35e7s^3+4.9e8s^2+4.8e9s+11.77e10}{s^7+193.3s^6+1.12e4s^5+2.7e7s^4+3.26e6s^3+2.81e7s^2+1.85e8s+3.2e8} \quad (1.16)$$

STEP 3:

- We then minimize the order of this controller to 1^{st} order by approximate pole-zero cancellations.

Poles of observer-controller	Zeros of observer-controller
-114.23	-114.32
-35.87	-35.36
-26.71	-26.72
-13.18	
-0.613+9.58j	-0.48+9.6j
-0.613-9.58j	-0.48-9.6j
-2.42	-3.02

- Thus, we are left with a single pole **-13.18**. So, the VR is given by:

$$V(s) = 33.25[\frac{480}{s+13.18}] \qquad (1.17)$$

- We find that step response is identical except that due to minimization of order, oscillations are introduced in the 1_{st} order VR. We introduce PSS loop for stabilization.

b) ***Design of PSS:***

STEP 4 :

- Introducing PSS makes the system transfer function to 11^{th} order. Thus we get the state space model given by A_g, B_g, C_g, D_g.
- From the root locus plot, we find that the dominant complex pole is **(-0.48 ± 9.6j).**
- For faster response, We shift it to: **(-1.5 ± 9.6j),** leaving all other poles unchanged. Using MATLAB, we get the controller gain matrix K_c=acker (A_g, B_g, mod_poles).For the observer design, we choose the poles as (**-1.5 ± 9.6j)** so that it decays faster.
- K_o=place (A_g', C_g', poles_obs)'.Thus we get the 11_{th} order observer-controller as:

  A_o= A_1-(K_o*C_1) – (B_1*K_c)

  B_o= K_o

  C_o= K_c

  D_o= 0 (1.18)

- We minimize this PSS from 11_{th} to 5_{th} order by approximate pole-zero cancellations.

$$\frac{-20s^4-4120s^3-51580s^2-10440s-540}{s^5+39s^4+507s^3+6183s^2+1112s+57} \qquad (1.19)$$

STEP 5 :

- Using MATLAB we tabulate all the poles and zeroes and check for cancellations

Poles of observer controller	Zeros of observer-controller
-114.30	-114.32
-36.106	-35.4
-20.9+16.3j	-18.15+16.3j
-20.9-16.3j	-18.15+16.3j
-28.61	-193.03
-26.74	-26.72
-5.02+13.7j	
-5.02-13.7j	
-3.62	-3.10
-0.091+0.03j	-0.105
-0.091-0.03j	-0.100

- We incorporate these poles and zeros for the 5th order PSS .After implementing the PSS.
- We plot the root locus of the damping loop.
- From the previous root locus plot, we find that the 5th order PSS manifests a pure damping at the dominant pole as the angle of departure is approximately= 180º. The gain for ζ=12% is found to be 0.84.

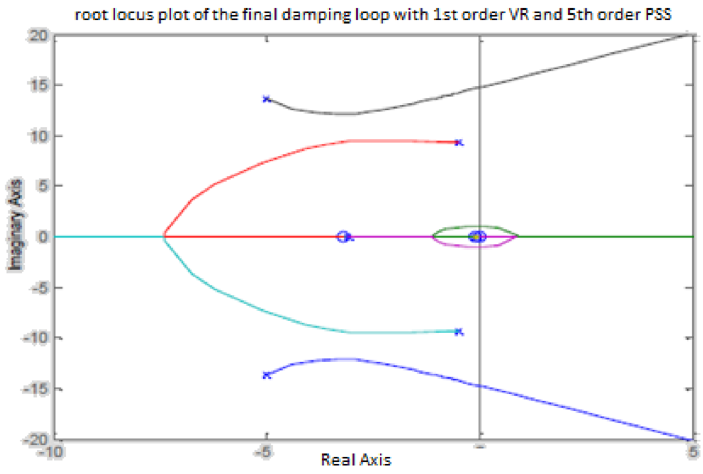

Fig. 3.13 Root locus plot of the damping (PSS) loop with 5th order PSS implemented

<u>STEP 6 :</u>

- Finally, we implement the above design in the SIMULINK model and find the step response. It is shown in figure 3.15

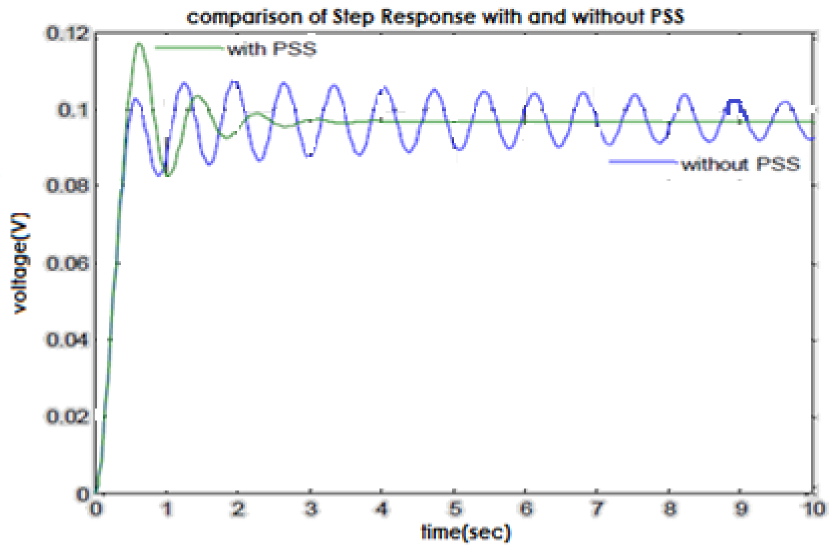

Fig.3.14 Comparison of the output response of system with and without PSS

The state space design of PSS is in general very much complex and real time modeling is close to impossible. But with pole-zero cancellations and small assumptions we can decrease the order of the system significantly and find impressive results as done here.

3.3 COMPARATIVE STUDY OF CONVENTIONAL DESIGN TECHNIQUES

Having incorporated various basic methods for design of PSS we can now have a comparative study of all these methods and discuss their merits and demerits. The design of Automatic Voltage Regulator (AVR) includes a constant voltage source (here a step input) implementing the regulation loop in each case and conclude that even when the Rise Time(t_r) , Peak Overshoot(M_p) , Settling time (t_s) and Steady State Error e_{ss} constraints are satisfied, the system is not perfectly damped and there are oscillations in it. Hence, we design a feedback loop (PSS) controlling rotor velocity $\Delta\omega$ as input and reducing oscillations.

- For PSS design using root-locus method; we find the dominant complex pole (swing mode) from the root locus plot of the open PSS loop and calculate the angle of departure from this pole. For perfect damping, we need angle of departure to be -180. Hence we design a lead-lead compensator to adjust the angle of departure. This method is elegant and simple, yet manual calculation and plotting is required to find the zero and pole of the compensator.

- Using frequency response-method, we have to decompose the system into its damping component to perform the analysis [1], figure.8. Hence it requires the detailed understanding of the power-system model and its states. Then we manipulate the phase of the system in a frequency range (2rad/sec to 20rad/sec) by a lead-lead compensator to achieve the desired damping effect. Again, this does not give an idea about the actual time-response characteristics and we have to perform a root locus analysis again to find the Gain for the specified damping.

- Last but not the least, in the state-space method, an exact 11^{th} order controller is derived from a full order state-observer. This is highly expensive and impractical, and thus we need to minimize the order of the system by approximate pole-zero cancellations which make it a viable and alternate solution leading to precision.

CHAPTER **4**

WIDE AREA CONTROL

4.1 INTRODUCTION

In the past years, continued load growth without a corresponding increase in transmission capacity has resulted in reduced operational margins for much power worldwide, and has led to operation of power system closer to the stability limits [1]. Likewise load transmission and distribution of power from distant generators to local load customers has become a common practice. This has led to substantially increased amount of power being transmitted through the existing bottlenecks and electromechanical oscillations of electric power system. The mechanism by which interconnected synchronous machines in large power system maintain synchronism is through restoring forces which act whenever these forces tend to accelerate or decelerate one or more generator with respect to one another. PSS are provided to add damping torque to generator oscillations by modulation of generator excitation signal.

4.2 NEED FOR MODERN APPROACH

The conventional PSS was first proposed in mid-20th century based on a linear model of the power system to damp the low frequency oscillations. But they are designed to be operated under fixed parameters derived from the system linearized model. The inherent nonlinearity in the modern 21st century complex loads, power system becomes a major source of model uncertainty. The system deterioration starts with alarming changes in steady-state parameter variations and gradually evolves to faster dynamic phenomena with the system reacting quickly and defending itself with pre-determined protection schemes and relays setup in a large inter-connected grid system. The main problem arises when locally measured quantities often are insufficient for detection and control of power system oscillations [11]. The possibility of strong coupling between local modes and the inter-area modes would make the tuning of local PSSs for damping all modes nearly impossible when there is no supervisory level controller.

4.3WIDE AREA CONTROL

Wide area control addresses automatic healing capabilities to some extent by proposing smart topology changes and control actions. Dynamic islanding and fast load shedding are schemes available to maintain as much as possible a healthy transmission system. New distributed instrumentation technology using accurate PMUs has been developed in recent years to become a powerful source of wide-area dynamic information. It is found that if remote signals from one or more distant locations of the power system can be applied to local controller design, system dynamic performance is enhanced. In order to attain such goals, it is desirable to systematically build a robust wide area controller model within an autonomous system framework. Sequential optimization procedure is used to tune the PSS global and local control loops.

4.4 PHASOR MEASUREMENT UNIT

PMU quantities are collected and concentrated for further exploitation in a PDC (Phasor Data Concentrator),from where the information is sent to a central place for EMS (Energy management System) use. The applications use the information to improve the results, detect problems and consequently trigger emergency control actions via remote-control and SCADA (Supervisory Control and Data Acquisition)/EMS. Within this context the operator could get a quick and reliable assessment of the system under stressed or chaotic conditions to determine:

- System security under large disturbances and unexpected events, and
- System subjected to an emergency state that can lead to restorative conditions

PMU can run at the scan rate at the substation level and every minute at the wide-area level to assess the security with the latest information from the field. It has been proved that the PMU technology had a positive impact regarding:

- Accuracy
- Convergence
- Observability
- Bad data processing

The PMU must be accurately synchronized, as all measurements must be around the milliseconds (or microseconds) time frame. If the PMU technology is used there must be a definition about how much information can be send and where to allocate the devices. The biggest problem right now is communication, it seems like not all the customers have enough infrastructures and there are very few utilities that do have and can actually get the data out of the substation. A uniform set of synchronized measurements across the system, let us say once a minute is pragmatic. Anything faster than that is practically very difficult to achieve, since there are interfering delays involved in data transfer; it takes something around 5 to 30 seconds to get the data back to the center. For faster application (dynamic analysis) high-speed links, proper priorities setup and a lot of data processing and handling must take place. The main issue is the cost of investment in the communication to handle PMU all over the grid. PMUs have substantial advantages in that they provide continuous, fast, and accurate time synchronized data for virtually any voltage and current phasors in the system. The generators along with PMUs in Wide area control are provided in nearly ideal circumstances where data are continuously transferred and monitored in a secure region. The secure region is constrained by the following set of limits:

- Relay settings
- Thermal limits
- Transient voltage dip/rise
- Small-signal stability
- Frequency stability

4.5 STRUCTURE OF WIDE AREA CONTROL

Instead of using exclusive communication lines, communication in WAMSs is based on powerful wide area network(WAN)/local area network (LAN) technology. PMUs sample AC waveforms with a sampling rate of several thousand hertz. By the discrete Fourier transform (DFT), PMUs calculate in real time the phases and amplitudes of the AC waveforms, and then the data packets including the phases and amplitudes are sent out through LAN/WAN at a speed from dozensupto100 frames/s (at a rate 10mS). Such a closed-loop system is often referred to as a networked control system (NCS), whose control loops are closed through real-time networks [12].

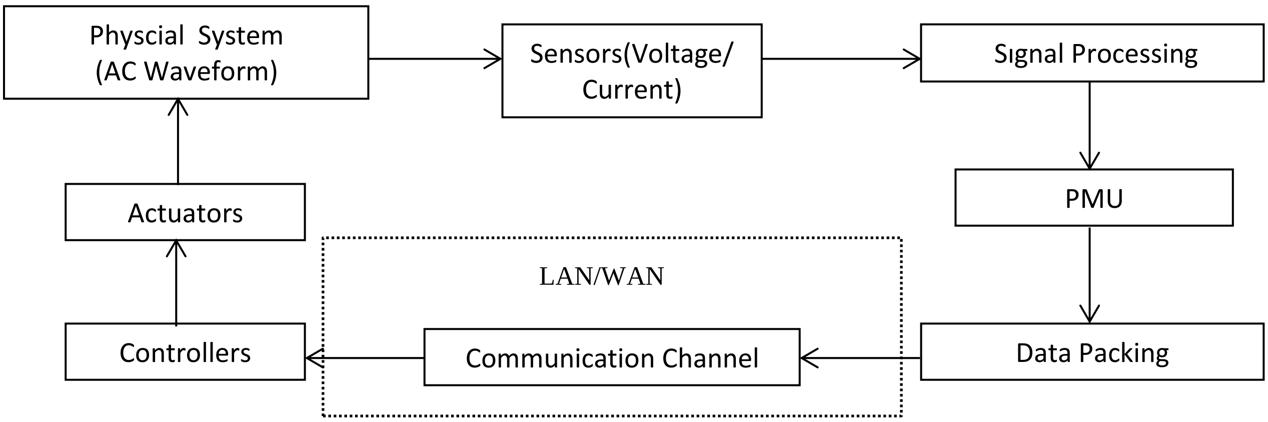

Fig. 4.1 Structure of WAMS-based closed-loop power systems

As the name suggests, WAMS control multiple generators and buses precisely and simultaneously. The sensors play a vital role sensing analog continuous data and feeding it to the Sampler. The discretization starts from here itself. The PMU’s take phasor measurements from various generators and buses and phasor difference is calculated based on the GPS

(Global Positioning Systems) technology. The phasor calculation is done and PMUs play a vital role here. Data are then encrypted and encapsulated sent to the central controlling system or SCADA. The transfer of data from local grids to central control and monitoring system are done via LAN/WAN as shown in the Fig 3.16. The protocols used in the transmission network are TCP/IP (Transmission Control Protocol/ Internet Protocol).The biggest problem is faced is the noise in the communication channels along with the random errors propagating in the Network. The problems are described in the next page. Data from various grids are stored and assessed continuously. They are monitored and compared with the reference ideal situation and corrective measures are decided. The controllers, via communication channels stimulate the actuator to take the required action and hence the instability is stabilized. The main role played apart from the sensors and controllers are by the Network (Data transferring/receiving).

4.6 NETWORK CONTROL SYSTEM (NCS) MODEL

NCS forms a vital part of the whole WAMS and it suffers from multiple setbacks. It controls the most important parameter that decides the effectiveness of the system i.e. the speed of response.

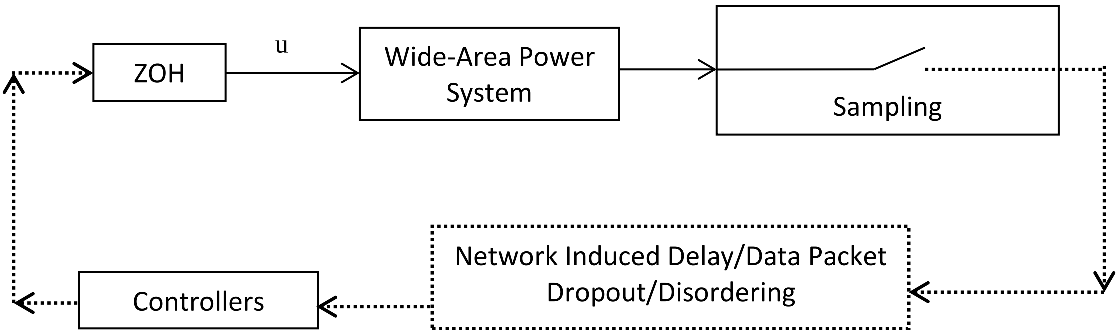

Fig. 4.2 NCS model for WAMS-based power system control[18]

The standard Zero-Order Hold (ZOH) operation is used in the control loop so that the states before communication failure can be held and continue to be used as feedback signals when communication disruption takes place. In the research area of wide-area control of power systems, guaranteed performance control of multi-machine power systems are being studied. References [16] and [18] discussed time delay issues in WAMS based control of power systems, but the models used were too simple to capture the time-varying nature of network-induced delays, data packet disordering, and dropout. In fact, the existing delay models which are used in WAMS-based control of power systems are all constant delays with known lower and upper bounds. Thus stability results derived based on such delay models may not work when time-varying delays are present. How to design wide-area controllers for power systems with more practical time-varying delay models is still challenging. From the perspective of NCSs, WAMS-based power system control mainly involves the following problems.

4.6.1 Network-Induced Delays

Network-induced delays occur while transmitting and/or receiving data among devices connected to the shared medium [13][14] due to delays offered by individual network components/devices. In general, the response time of fiber optic digital communication is approximately 38 milliseconds; while latency using modems via microwave is over 80 ms [15]. This delay, either constant or time varying, or even random, may degrade the performance of control systems designed without considering delays and may even destabilize the system [13].

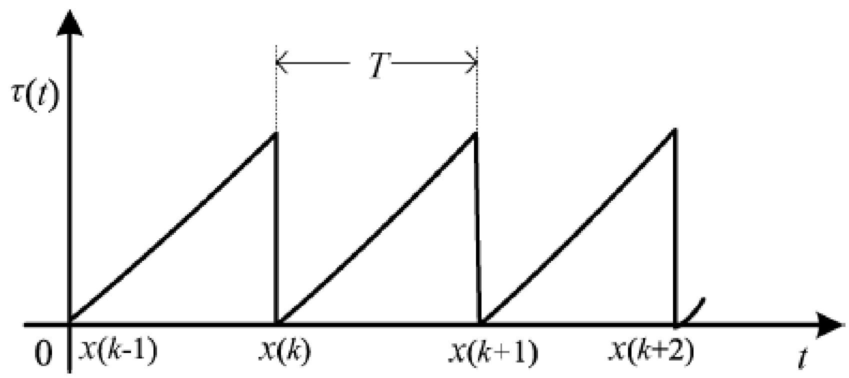

Fig. 4.3 Time Delay in Ideal networks[13]

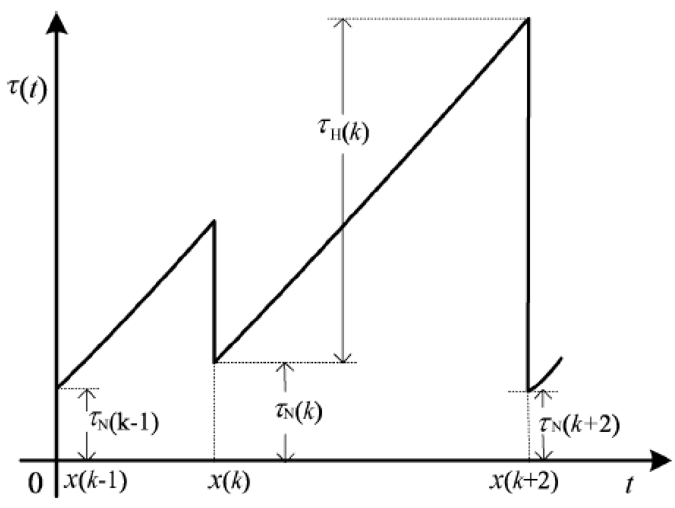

Fig. 4.4 Time Delay in real networks.[13]

where Fig 3.18 shows the network induced delays without taking into considerations the real time problems such as Data packet dropout and Data packet disordering . Fig 1.21 discusses the real time situations where we do consider all the real time induced delays, data packet dropouts and data packet disordering. If the data packet $x_{k+1}$is lost then the packet x_k will be held until the next packet is fetched. Using sample and hold process, the packets are being held to increase the time period resulting in a time varying delay.

During the period the network induced delays experienced by the data packets is different for different packets but they induce a positive delay because it behaves as a real system.

4.6.2 Data Packet Dropout

Due to the randomness and noises in communication channels, there exist inescapable errors in the transmitted data packets or even loss. Despite modern devices are equipped with transmission-retry mechanisms, yet they can only send limited data over stipulated time period. Whenever time exceeds this limited period, the packets will be dropped and lost and can never be retrieved [13].This possess a potential threat to the performance and efficiency of the overall system dynamic response [12].

4.6.3 Data Packet Disordering:

Large inter-connection of networks provides huge number of paths available for data transfer. Data packet disordering may develop anywhere between the transmission end and the receiving end and vice-versa; different data packets may experience different amount of time delays, which may lead to circumstances where data sent earlier may reach the destination later. This is called “data packet disordering” [18]. This is also regarded as one of the three areas of concern in WAMS-based power system control.

As a new research area, NCSs have attracted much attention recently in which networked control problems is of central focus. For example, discrete-time model, stabilization of linear systems over networks with bounded packet loss and uncertainty in NCSs has attracted numerous researchers for possible real time solutions. A model-based networked control scheme was designed in [16],in which, given the system model, the system states were generated by the model to compensate for the cases when measurements failed to be sent over the communication network. Another fault-tolerant control strategy was developed in [9]in which the process had to run open loop when communication disruption occurred.

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 CONCLUSION

Without ubiquitous, accurate, and reliable real-time sensors, the electric grid fails in terms of reliability, efficiency, and capacity to manage the unprecedented number of variable energy sources and loads necessary to meet the vision for the Smart Grid. Continued load growth without a corresponding increase in transmission resources has resulted in reduced operational margins for many power systems worldwide and has led to operation of power systems closer to their stability limits and to power exchange in new patterns. These issues, along with the on-going worldwide trend towards deregulation of the entire industry on the one hand and the increased need for accurate and better network monitoring on the other hand, eventually forces power utilities to be exposed to this pressure to demand new solutions for wide area monitoring, protection and control. This method minimizes outages, lowers risk of power system instabilities, increased transmission capabilities, and optimized power flow to improve congestion management.

5.2 FUTURE WORK

With increasing power demand and load complexity, wide spread research have been conducted throughout the globe. What awaits is an economically viable and sustainable solution which would solve our cause. The present paper has provided one such solution-WAC. WAC has already been installed in certain western and European countries and is yet to be implemented in India. Future work can be based on further evolution of this technology using True Time Simulations. WAC can effectively lead to globalization of grids and can solve power crisis by implementation of advance algorithms. Yet this is a new technology and loads of research can be done on it. WAC can be implemented initially from two area four machine configuration to 14 bus and then to 30 bus system. It can be tested for all type of loads and with increasing complexity. WAC gives us a challenge as it can be the greatest platform ever made and can lead to an innovative and new generation.

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APPENDIX

1-Generalized 7th Order States [17]:-

$$A = \begin{bmatrix} 0 & 377.0 & 0 & 0 & 0 & 0 & 0 \\ -0.245 & -0.156 & -0.136 & -0.123 & -0.0125 & -0.05460 & 0 \\ 0.109 & 0.262 & -2.17 & 2.30 & -0.171 & -0.0753 & 1.27 \\ -4.58 & 0 & 30.01 & -34.30 & 0 & 0 & 0 \\ -0.161 & 0 & 0 & 0 & -8.44 & 6.33 & 0 \\ -1.70 & 0 & 0 & 0 & 15.2 & -21.5 & 0 \\ -33.9 & -23.1 & 6.86 & -59.5 & 1.5 & 6.63 & -114 \end{bmatrix}$$

$$B = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 16.4]^T$$

$$C = \begin{bmatrix} -0.123 & 1.050 & 0.2301 & 0.207 & -0.1050 & -0.460 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1.42 & 0.9 & 0.787 & 0.708 & 0.0713 & 0.314 & 0 \end{bmatrix}$$

2- The model for G_w i.e. effect of speed on electrical torque due to machine dynamics

$$A_w = \begin{bmatrix} 0 & 376 & 0 \\ -K & -D & a_{23} \\ a_{31} & a_{32} & A_{33} \end{bmatrix}$$

The model of the damping loop is :-

$\xi' = A_{33}\xi + a_{32}\omega$

$\tau = a_{23}\xi$

where, K=0.2462 D=0.1563

$$A_{33} = \begin{bmatrix} -2.17 & 2.30 & -0.0171 & -0.0753 & 1.27 \\ 30.0 & -34.3 & 0 & 0 & 0 \\ 0 & 0 & -8.44 & 6.33 & 0 \\ 0 & 0 & 15.2 & -21.5 & 0 \\ 6.86 & -59.5 & 1.5 & 6.63 & -114 \end{bmatrix}$$

$$a_{32} = \begin{bmatrix} 0.262 \\ 0 \\ 0 \\ 0 \\ -23.1 \end{bmatrix}$$

$$a_{23} = \begin{bmatrix} -0.1370 & -0.1230 & -0.0124 & -0.05461 & 0 \end{bmatrix}$$